World Class University (WCU) Project Application Form

2010 WCU Project Mid-Term Evaluation (Type 2)

Part A. General Information

Type of Project	(X) Recruiting foreign scholars to existing academic programs		
Proposal No.	R32-10045		
Project Title	Fundamental studies with Bose-Einstein condensates and their applications		
Principal Investigator	Full Name	Kyungwon An	
	Affiliation(Univ.)	Seoul National University	
Research Field Classifications	Proposed Field[1)]	Breakthrough Technology	
	(X)Natural Science ( )Life Science ( )Engineering ( )Humanities & Social Sciences		
Related Sub-field[2)]	Atomic Physics	Superfluidity	Optics
Relative Importance (%)[3)]	30	30	25
Project Duration	from 12/01/2008 (mm/dd/yyyy) to 8/31/2013 (mm/dd/yyyy) (5 years)		

1) The principal investigator is required to provide a description of the proposed field (Ex: Financial engineering, Energy/Environment, NBIC fusion tech., Bio Pharmaceutics/Biomedical engineering, Etc.)
2) Refer to the field classification table provided by NRF
3) Assign percentages to the relevance of each sub-field. The percentages of all sub-fields need not total 100 percent.

A-2. Participants

1) Principal investigator (please attach short vitae, not to exceed 4 pages)

No.	Full Name	Major field of study
1	Kyungwon An	atomic physics/ quantum optics
	Role in the project	
	Prof. An as a principal investigator (PI) will lead the group and provide various supports to the participating scholars for the success of the project. He has been a PI of several projects (Creative Research Initiative, National Research Laboratory, Pure Basic Science, etc) of similar size to the present project in the past 10 years in Korea. His expertise in the cavity-QED microlaser, single-atom traps and quantum chaos in microcavities will be useful for carrying out the proposed studies. He will work together with Dr. Shin in creating BECs and will play a major role in cavity-QED/quantum information experiments and quantum chaos experiments with BECs working closely with Prof. Jeong.	

2) Korean Participants (please attach short vitae, not to exceed 4 pages per participant)

No.	Full Name	Major field of study
1	Hyunseok Jeong	quantum optics/ quantum information
	Prof. Jeong will provide a theoretical support for the proposed experiments with his expertise and knowledge of quantum information theory, theoretical quantum optics, and foundations of quantum theory. His expertise on these subjects will be immediately useful for the quantum information study with BEC: generation of macroscopic quantum superposition/entanglement and quantum information processing by using BECs and optical systems.	

3) Foreign Participants (please attach short vitae, not to exceed 4 pages per participant)

No.	Full Name	Major field of study
1	Yong-il Shin	atomic physics (BEC experiment)
	Role in the project	

	There is no BEC experiment group in Korea. Hence, the main role of Dr. Shin is to introduce and activate the BEC experiments and to educate/train graduate students at SNU to be a researcher in this field. Shin has participated in various quantum gas experiments at the Ketterle group at MIT. His major scientific achievements include first demonstration of a trapped BEC interferometer, first observation of decay of a doubly-quantized vortex in BEC, and observation of phase separation of a superfluid and a normal gas. Recently he has successfully performed a series of experiments with strongly interacting Fermi mixtures in collaboration with Wolfgang Ketterle at MIT, defining the frontier of the current Fermi gas experiments. Through the research activities in this WCU program, he will make an essential contribution to establish an active BEC community in Korea.

Part B. Project Description

Keywords	Bose-Einstein condensate	strongly correlated material	superfluidity
	quantum information	matter wave	quantum chaos
	superconductivity	Schroedinger's cat	scar mode
Research Goal	- To realize Bose-Einstein condensates by laser trapping and cooling of neutral atoms - To understand many-body physics in strongly interacting fermion/boson systems - To realize macroscopic superposition and entanglement with BEC for quantum information applications - To realize matter-wave scar modes of ultracold atoms for quantum chaos studies		
Research Contents	Bose-Einstein condensates can be realized by cooling neutral atoms down to a nano Kelvin range with laser trapping and cooling techniques. With ultracold atoms in BEC we can study many important physical phenomena to which the conventional approaches have severe limitations. Particularly, complete control of experimental parameters and the spectroscopic precision of atomic physics make the ultracold atoms in BEC ideal for direct examination of many theoretical predictions. Related to condensed matter physics, experimental study of strongly interacting fermion/boson systems is proposed: study of Fermi-Hubbard models by using optical lattices and its application to high temperature superconductivity, and fermionic superfluidity and pair correlations in strongly interacting Fermi gases. Related to quantum optics, we propose to study macroscopic superposition and entanglement such as atomic Schrödinger cat states by using coherent interaction of BECs with a high-Q microcavity and to explore its application to quantum information. Moreover, experimental and theoretical investigation of matter-wave scar modes of ultracold atoms trapped in a light potential with asymmetric boundary is proposed as a new platform for quantum chaos studies.		
Expected Research Outputs	- To have our own, Korea's first BEC for the pride of Korea's science and technology - To advance our research capacity to the level of the leading nations in the related fields of condensed matter physics, quantum information and quantum chaos - To acquire home-grown techniques in precision measurement, atomic clock and quantum computation - To build our own BEC research community which does not exist so far		

Note: This page should match the summary of Proposal from Application Form from Selection Evaluation. Summary should *__not exceed 1 page__*

Part C. Progress Report (Parts C~D not to exceed 20 pages)

C.1. Research Status

The purpose of our WCU research program is to realize Bose-Einstein condensates (BECs), which are new quantum state of matter never achieved before in Korea, and to investigate their diverse quantum applications for fermionic superfluidity, quantum chaos and quantum information. During the first phase of the program, we have constructed a new experimental apparatus for BEC production and have succeeded in observing the first BEC in Korea. This achievement fully accomplishes the primary goal of the starting phase, providing a solid platform to launch the second-phase program, which is carefully designed for the aforementioned BEC applications.

In the following, we describe the details of our work.

C.1.1 Fast and efficient production of Bose-Einstein condensates

We have constructed a new BEC apparatus and demonstrated a rapid and efficient production of sodium condensates. Bose-Einstein condensation in an atomic gas occurs at extremely low, nano(10^{-9})-Kelvin temperature due to the diluteness of the atomic gas. Therefore, an experimental apparatus for BEC production needs to be carefully designed to apply various cooling techniques such as laser cooling and evaporative cooling in a precise and controlled manner. Our BEC machine employs a zero crossing Zeeman slower, designed to generate a flux of over 10^{11} atoms/s (Fig. 1). Slowed atoms were collected in a dark magneto-optical trap and then transferred in a magnetic quadrupole trap. The Majorana spin-flip loss was optically suppressed by applying a focused, blue-detuned laser beam near the zero of the magnetic field. The pointing stability of the plug beam was improved by using a fiber. Finally, rf evaporative cooling was applied to the atoms in the plugged quadrupole trap. We have optimized the cooling procedure to generate a pure condensate with 10^7 atoms every 17 s (Fig. 2). This result is a remarkable improvement in the production efficiency considering the previous other BEC experiments, where one needs a longer, over 30 s, evaporation cooling time to produce a condensate of over one million atoms.

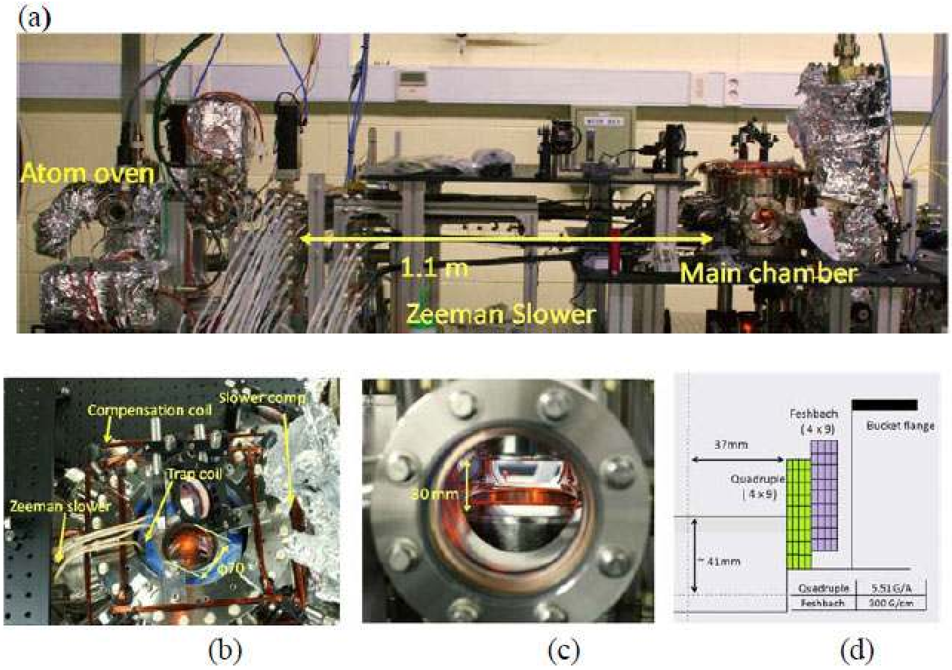

Fig. 1 Bose-Einstein Condensate (BEC) machine. (a) The vacuum chamber consists of atom oven, Zeeman slower and the main chamber. All vacuum parts have been assembled and maintained in ultra-high vacuum condition. Particularly the pressure of the main chamber reaches about $5\cdot10^{-12}$ torr with titanium sublimation pumping. The life time of an atom cloud in the main chamber is expected to be over 1 minute, which is beneficial to stable operation of evaporative cooling. Top (b) and side (c) view of the main chamber. The main chamber is featured by the wide optical access, allowing for high-resolution imaging and advanced Raman spectroscopy. The top and bottom flanges of the main chamber have recessed bucket windows with 70mm-diameter clearance, providing a large numerical aperture of 0.58. (d) The magnetic coils are placed in these bucket flanges. Magnetic coils used for quadruple field, Feshbach field and bias field are held together with epoxy. These coils are made close to atoms through the bucket windows. Two pairs of RF coils are wound inside the chamber for transverse control of RF field, which might be helpful to generate various types of RF-dressed traps

In order to understand the fast evaporation dynamics, we have investigated the effects of the Majorana loss and the plug by measuring the loss rates and the resultant heating rates for various conditions. The average loss energy of a spin-flipped atom shows an almost linear dependence on temperature and is determined to be about 60% of the average energy of a trapped atom. For a plugged trap, the reduction factor in the loss rate is found to be exponentially proportional to a Boltzmann factor. This confirms that the plugging effect results from density suppression due to the repulsive optical potential in the loss region. Finally, we have developed a numerical model for quantitative description of the evaporation dynamics in a plugged quadrupole trap (Fig

3). We expect that this model will be helpful to develop and optimize evaporation processes using a magnetic quadrupole trap.

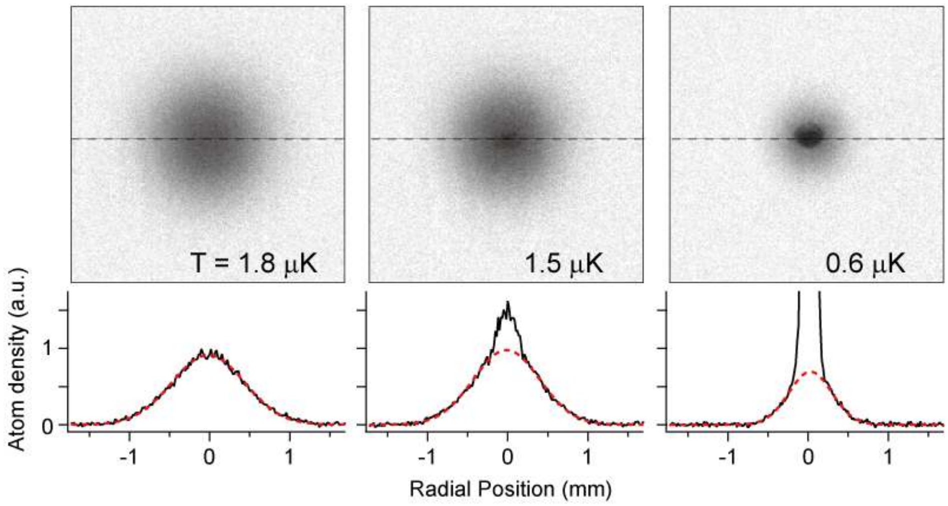

Figure 2: Bose-Einstein condensation. The absorption images of atom clouds after time-of-flight. At low temperatures, the bimodal momentum distribution is observed, indicating the phase transition. The bottom graph is the radial atom density distribution along the center line in the image. The red dash line is a Gaussian fit to the outer thermal gas.

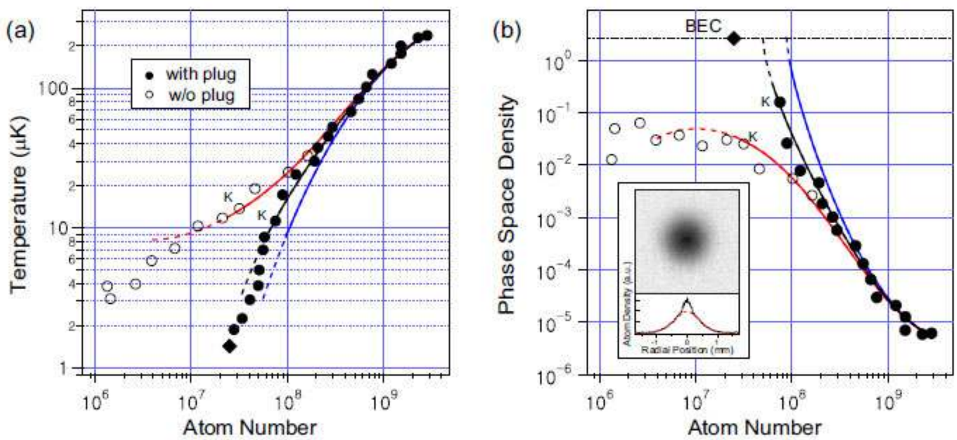

Figure 3: Evaporation cooling in an optically plugged quadrupole trap. Evaporation cooling is performed by removing high-energy atoms from a trapped gas using rf transition. Evaporation trajectory in the parameter plane of (a) temperature and atom number, and (b) peak phase space density and atom number. The onset of Bose-Einstein condensation is observed from the bimodal momentum distribution in an time-of-flight absorption image (see inset). The black diamond indicates the phase transition point. Without the plug, the maximum phase space density is about 0.05, which is much less than the critical value for Bose-Einstein condensation.

C.1.2 Second-phase plan for strongly interacting Fermi gases

Our BEC apparatus will be upgraded for the study of a strongly interacting Fermi gas of lithium-6 atoms. Lithium atom has broad Feshbach resonances between the three lowest hyperfine spin states, which is necessary for stable control of the scattering length of atoms. It is found that any binary mixture out of the three lowest hyperfine states can form a superfluid with a long life time. A degenerate Fermi gas of lithium atoms will be prepared using laser cooling and sympathetic cooling with sodium atoms. Currently, we are developing a new laser system for lithium atoms. With the upgraded Bose-Fermi machine, we will investigate pairing and fermionic superfluidity in an asymmetric Fermi mixture to search for new exotic ground states such as the Fulde-Ferrell-Larkin-Ovchinnikov state.

C.1.2.1 Pairing in normal phases

In a Bardeen-Cooper-Schrieffer (BCS) superfluid, pairing happens together with superfluidity, i.e. a normal phase above a critical temperature is a Fermi liquid with no pair correlations. However, in high-T_C superconductors pairing gap is observed even above a critical temperature, named as ‘pseudo gap’ . The BEC-BCS crossover theory suggested one possible answer for this anomalous behavior of the normal state that the pseudo gap is the manifestation of non-condensed preformed pairs. In the BEC (strong coupling) limit, two fermions are tightly bound to form a composite boson so that a normal phase is a thermal gas of bosonic dimers. The evolution of the normal phase from a Bose liquid to a Fermi liquid is one of the important issues in the BEC-BCS crossover physics. Another intriguing regime is the normal phase above the Chandrasekhar-Clogston (CC) limit. Recently, it has been experimentally observed that a bosonic dimer can be destabilized in a deep Fermi sea of one of its constituents due to the degeneracy pressure. Pair correlations and possible non-Fermi liquid behavior over this strongly interacting normal regime will be addressed in our study.

C.1.2.2 Polarized superfluid states

In an asymmetric situation, an interacting Fermi system might find a new ground state. Exotic, polarized superfluid states have been predicted in a two-component Fermi gas system. In the breached-pair state, some of minority fermions move up to the majority Fermi surface level to form pairs and the excess majority fermions form a two-Fermi-surface liquid. This is a gapless, homogeneous polarized superfluid. In the inhomogeneous Fulde-Ferrell-Larkin-Ovchinnikov (FFLO) state, the order parameter has spatial periodic modulation breaking rotation and translational symmetries. Actually, we have observed a polarized superfluid at finite temperature. Currently, we attribute the non-zero polarization to the thermal population of fermionic quasiparticles in the BCS-type superfluid. However, the microscopic properties of the polarized superfluid, e.g. the momentum distribution of the excess fermions and the gapless excitation spectrum have not been resolved yet at this intermediate temperature. Using spectroscopic methods, we will clarify the microscopic structure of the polarized superfluid and search for a new state.

C.1.2.3 Fermi gas in lower dimensions

Qualitatively different physics may arise in lower dimensions. For example, in one or two dimension a two-body bound state always exists with any arbitrary attractive interaction, which is not the case in free space. Furthermore, the role of quantum fluctuations is amplified in lower dimension to enhance correlation effects. Using optical lattice techniques, we will extend the study of strongly interacting Fermi gases to lower dimensions. In the view point of quantum many-body simulation, 1D physics has a special position in that there are many models which can be solved exactly using the Bethe ansatz method. An exactly solvable model of the BCS-BEC crossover in a quasi-1D geometry has been theoretically presented. Also, it has been shown that the parameter window for the FFLO phase becomes larger in the quasi-1D regime. Finally, this study will be extended to 3D optical lattices, aiming at realization of Heisenberg Hamiltonians for quantum magnetism.

C.1.3 Progresses toward quantum chaos quantum information studies with BECs

We have performed preliminary experiments to trap rubidium atoms with a dipole force trap and confirmed the trapping of rubidium atoms. At the same time, we have done experiments to measure extremely weak signal from single atoms. Specifically, we trapped a single atom in an optical lattice and measured the spectrum of the trapped single atom by using an ultrasensitive spectroscopic technique, called photon-counting second-order correlation spectroscopy. We observed the Lamb-Dicke effect, namely spectral narrowing due to strong position localization, and the line broadening due to matter-wave tunneling of a single atom to adjacent potential minima in the optical lattice. The results are summarized in a manuscript prepared for Nano Letters.

We have also done a series of experiments to couple a single atom to a high-Q microcavity. Among them, the observation of an exceptional point in an atom-cavity system is highly related to the quantum chaos study that we plan to perform with a BEC. An atom-cavity system is an open quantum system with energy loss. Therefore, under a special condition, the system is expected in theory to show an exceptional point at which the distinction between a crossing and an avoided crossing of energy levels disappears. We have already observed the existence of an exceptional point for the first time in a deformed microcavity, a classical system simulating an open quantum system [S. Lee *et al*, Phys. Rev. Lett. **103**, 134101 (2009), See Figure 4].

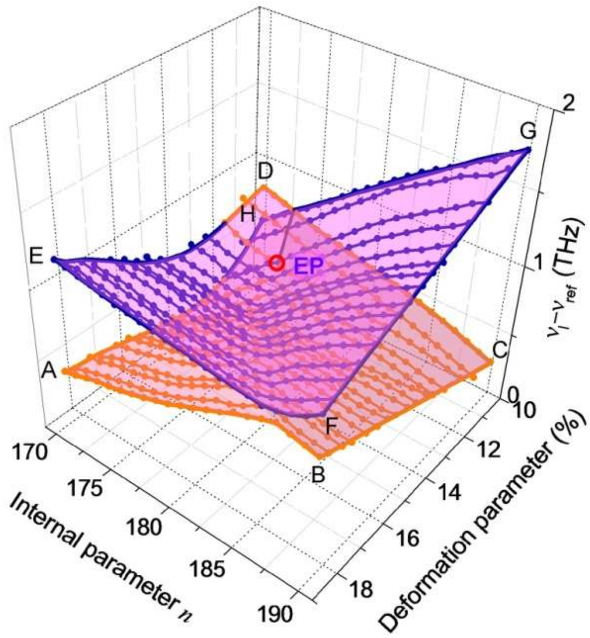

Figure 4: Exceptional point observed in a deformed microcavity and the topology of the nearby energy levels. The topology is the same as the Moebius strip. As a result, it is impossible to assign quantum numbers consistently.

In order to observe an exceptional point in the atom-cavity system, the atom-cavity coupling constant needs be varied continuously. We have found a way to accomplish this by employing an elliptically-polarized probe laser. We succeeded in observing an exceptional point by cooling the atoms down to a-few micro-K temperature by sub-Doppler cooling, coupling a single atom to the cavity and measuring the transmission spectrum of the combined system [Y. Choi *et al.*, Phys. Rev. Lett. **104**, 153601 (2010), See Figure 5]. This study paves a way to further study many interesting phenomena expected to occur at the exceptional point such as divergent spontaneous emission there. It also helps us to understand various open quantum systems better.

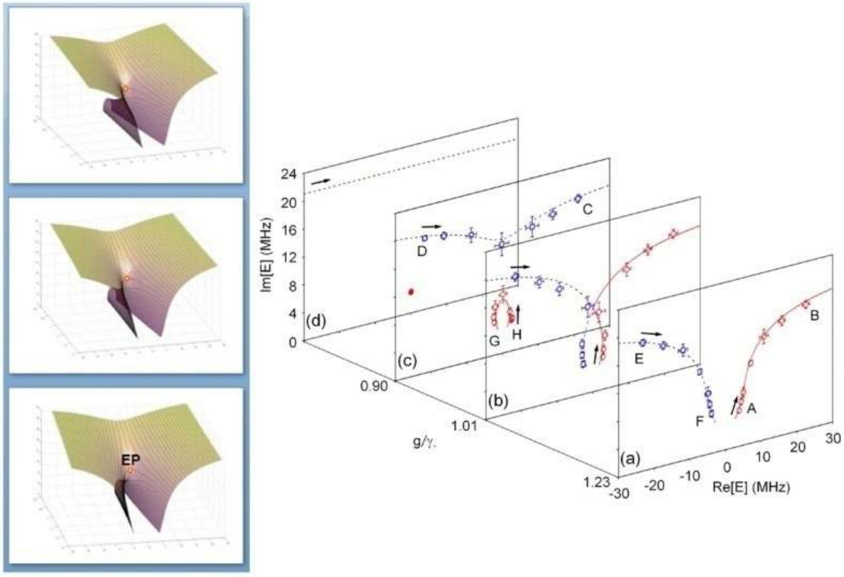

Figure 5: The complex-energy surfaces expected in theory and the actual surfaces observed in the experiment. Data in (b) correspond to the exceptional point, where two eigenstates coalesce into one. At the exceptional point the cavity transmission exhibits a critical behavior.

In addition, we have observed the pump-induced dynamical tunneling in a deformed microcavity laser for the first time [J. Yang *et al*., Physical Review Letters 104, 243601 (2010)]. This work is particularly important since it suggests dynamical tunneling would also occur in our planned quantum chaos study with a BEC by the same principle. In this experiment we observed the lasing threshold decreased by 1000 folds when chaotic modes of the microcavity is pumped by a pump laser whose frequency is resonant with a high-Q mode confined in a regular region in the phase space of the system. This phenomenon was made possible by the dynamical tunneling of the pump light in the chaotic modes into the high-Q mode in a regular region (Fig. 6). This study suggests the lasing threshold of microcavity laser can be greatly reduced by using dynamical tunneling process.

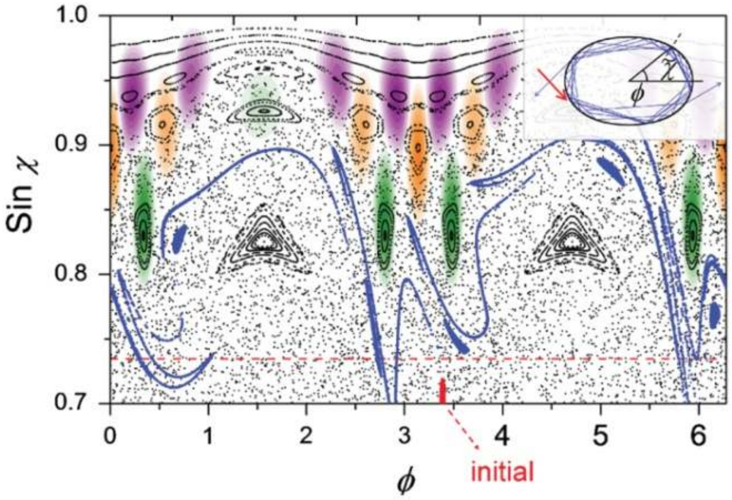

Figure 6: Dynamical tunneling from chaotic modes to a regular mode has been observed in a deformed microcavity laser when the frequency of light wandering in the chaotic regions(dots and blue lines) is resonant to a high-Q mode(purple, orange and green distributions) in regular regions.

C.1.4 Second-phase plan for quantum chaos quantum information studies with BECs

In the second phase of our research, we plan to contain a BEC in a cavity made by light. When a blue-shifted laser beam is rapidly circulated along a certain closed path surrounding a BEC, the atoms there would suffer repulsive force at the closed path, and as a result, would be confined inside the closed path. This is the mechanism of the atom cavity with two dimensional dipole potential barrier. Using two acousto-optic modulators (AOMs), we can make an arbitrary shape of cavity. Above the cavity, we will capture a BEC and release it, and then the atoms would fall down by gravity and expand inside the cavity. Using a CCD, we can image the formation of matter-wave modes inside the cavity (Fig. 7). In this procedure, we use non-destructive imaging method using diffraction of non-resonant light.

When temperature of atoms increases, the atoms would behave like classical particles with very short wavelength of matter wave. Therefore, we can control the condition of injected atoms, from single-atom classical particle to multi-atom quantum matter waves. We will investigate how the classical chaotic behavior evolves into quantum chaotic behavior. We are interested in physical phenomena appearing at the transition regime between classical and quantum worlds. Especially, we will explore the role of coherence and nonlinearity of strongly interacting ultracold bosonic/fermionic quantum gas in the quantum-classical transition.

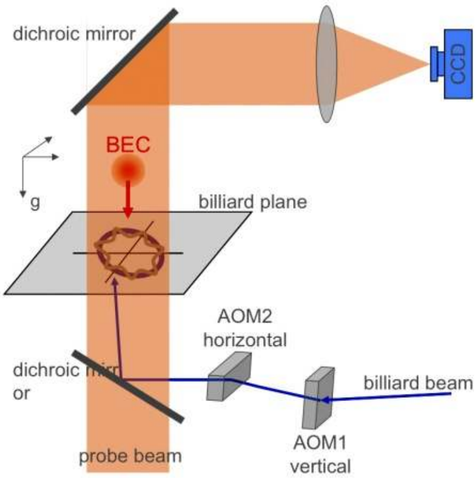

Figure 7: Blue-detuned laser beam is diffracted by two AOMs oriented orthogonally to each other and form a closed dipole-force potential barrier. A BEC formed just above the potential barrier plane (billiard plane) is released downward by gravity and interact with the potential barrier and eventually form matter-wave modes with a certain mater-wave resonance frequency.

So far, coupling between cavity and cold atoms rather than BEC has been attempted. We are planning to create the BEC directly in the cavity, and realize the strong coupling between the BEC and the cavity. Because all the atoms in the BEC will coherently interact with the cavity, the coupling constant will be greatly enhanced, and as a result nonclassical photon states can be generated. For example, the highly non-classical photon is to be generated through the coupling between the cavity and the BEC as a giant single atom. Particularly, the coupling of the strongly interacting Bose/Fermi gas and the cavity may lead to novel phenomena caused by strong nonlinearity and inherent quantum coherence. We will prepare a cavity which satisfies the strong coupling condition with single atoms, and trap many atoms outside the cavity. After polarization gradient cooling, we will transport the cold atoms into the cavity mode by means of optical conveyor belt, and then inside the cavity, trap the atoms with another dipole trap. Through evaporative cooling, which decreases the potential depth of the dipole trap slowly, the BEC can be created inside the cavity (Fig. 8).

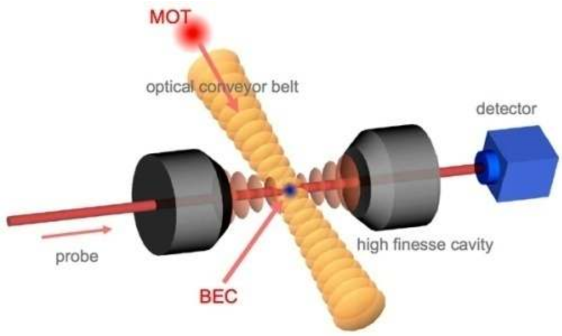

Figure 8: Schematic for cavity-QED experiment employing a BEC. Atoms trapped outside the cavity is transported into the cavity by an optical conveyor belt. By using a dipole trap and evaporative cooling atoms will be further cooled and condensed to a BEC. An off-resonant probe laser is used to monitor the coupling between the BEC and the cavity.

For quantum information application, we consider using interactions between BECs and optical systems for the generation of macroscopic quantum superposition and entanglement. We will use a BEC as a matter-wave mirror in a form of Bragg reflector. The BEC is then coupled with a single-mode or an entangled Schroedinger cat state of light, which is separately generated by all optical means. For macroscopic quantum superposition/entanglement with BEC, a single-mode Schroedinger cat state, represented as $c(|\sqrt{2}\alpha > + |-\sqrt{2}\alpha >)$ with $|\sqrt{2}\alpha >$ a coherent state of amplitude $\sqrt{2}\alpha$, is first generated and then divided at a 50:50 beam splitter, resulting in an *entangled* Schroedinger cat state represented by $c(|\alpha >|\alpha > + |-\alpha >|-\alpha >)$. One mode of the Schroedinger cat state is then mixed with an ancillary coherent state $|\alpha >$ at another 50:50 beam splitter (Fig. 9). If the incident state is $|\alpha >$, the total state after passing through the beam splitter with the ancillary state $|\alpha >$ will be $|\sqrt{2}\alpha >|0>$. On the other hand, if the incident state is $|-\alpha >$, the result will be $|0>|-\sqrt{2}\alpha >$. In either case, all the photons go to only one of the two opposite directions depending on the input photon states. As a result, a recoil momentum is transferred to either (left or right) side of the BEC mirror and therefore a macroscopic entanglement can be generated between the coherent states of light and the BEC atoms. In order to produce a macroscopic quantum superposition of BEC, it would be more efficient to use the single-mode Schrodinger cat state without the first beam splitter and the photodetector in Fig. 9. When the two-mode entangled Schroedinger cat states are used, one may perform various types of quantum measurements on the optical part to generate different kinds of macroscopic quantum superposition of BEC system.

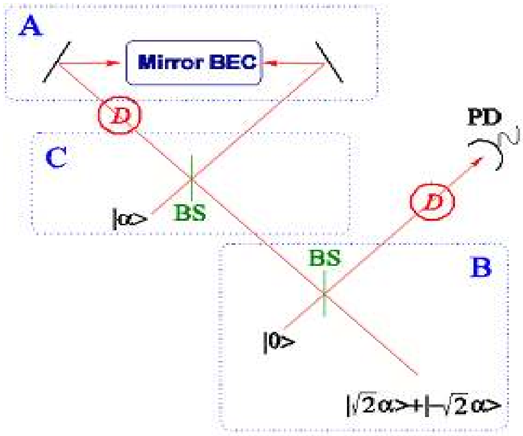

Figure 9: Generation of macroscopic quantum entanglement between a BEC mirror and a light field using the interaction between a Schroedinger cat state and BEC. **PD**: photodetector, **BS**: beam splitter, ***D***: displacement operation.

C.1.5 Theoretical progresses toward quantum information with BEC

In our research plan, we planned to develop theoretical tools to analyze macroscopic and many-body (multipartite) quantum superpositions and entanglement. We also planned to develop a generation scheme for macroscopic superpositions/ entanglement via the interplay between a Bose-Einstein condensates (BEC) and various optical states (single-mode and two-mode coherent-state superpositions, squeezed states, etc). We finally aim at suggesting possibility of quantum information processing using hybrid systems of the BEC and optical systems. Based on our research plan, we have developed strong theoretical tools to quantify macroscopic quantum superpositions/entanglement based on the phase-space formalism [Phys. Rev. A **81**, 012302 (2010)]. As multipartite macroscopic entangled states have complicated structures, it is generally very demanding to quantify entanglement of those states. Therefore, our new method will be very useful for the latter part our study where we will extensively analyze entanglement and related properties of macroscopic entangled states such as photon-BEC entangled states. Most recently, we have applied our techniques to bosonic systems and compared dynamics of entanglement between two bosonic particles and that of multipartite bosonic entanglement [quant-ph arXiv:1008.1279, See Figure 10]. We found that multipartite bosonic entanglement is relatively robust to decoherence compared to what is typically predicted from the previous results. Furthermore, we have found a previously unknown method to efficiently detect macroscopic entanglement using fuzzy measurements [Phys. Rev. Lett. **102**, 060403 (2009)]. We have also tested a newly developed generation scheme for macroscopic entanglement, and have applied it to the world-first direct experimental demonstration of the bosonic commutation relation [Phys. Rev. Lett. **103**, 140406

(2009), See Figure 11]. We have developed a generation scheme for multipartite macroscopic entanglement using interactions between microscopic and macroscopic field modes, and analyzed their nonlocal properties [Phys. Rev. A **82**, 022315 (2010)]. This general scheme may be applied to specific physical processes including interactions between photonic qubits and a BEC.

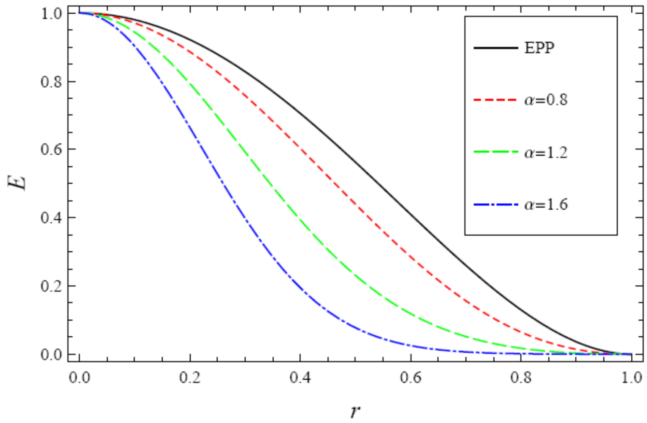

Figure 10: Dynamics of entanglement between two bosonic particles (black) is compared with that of multipartite bosonic entanglement for several different cases of the "alpha" parameter which indicates the size of the system.

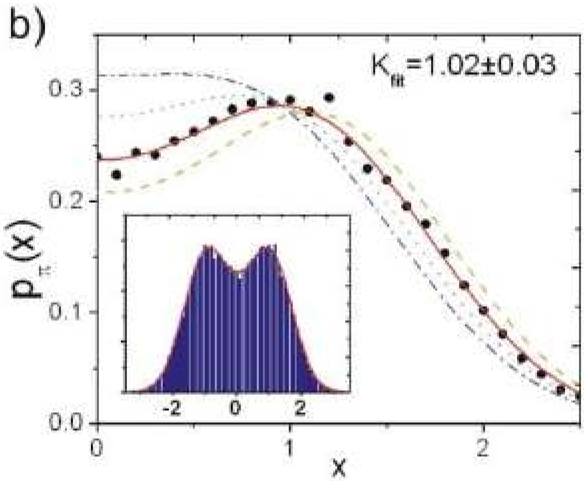

Figure 11: The world-first experimental demonstration of the bosonic commutation relation using our new scheme for the generation of macroscopic entanglement.

We are currently studying generation schemes for macroscopic entanglement using matter-field interactions and analyzing states that can be generated by those schemes including their nonlocality (Fig. 12). In particular, we are analyzing our own model suggested in the research plan using the interaction between BEC and small superpositions of optical coherent states. Using the method we have developed so far, we are trying to analyze various characteristics of entangled states generated using this method, which involves heavy numerical calculations. The characteristic of the entangled states that we are interested in include degrees of entanglement, quantum nonlocality (violation of local realism) verified by violation of Bell's inequality, and violation of macro-realism verified by violation of Leggett-Garg inequality.

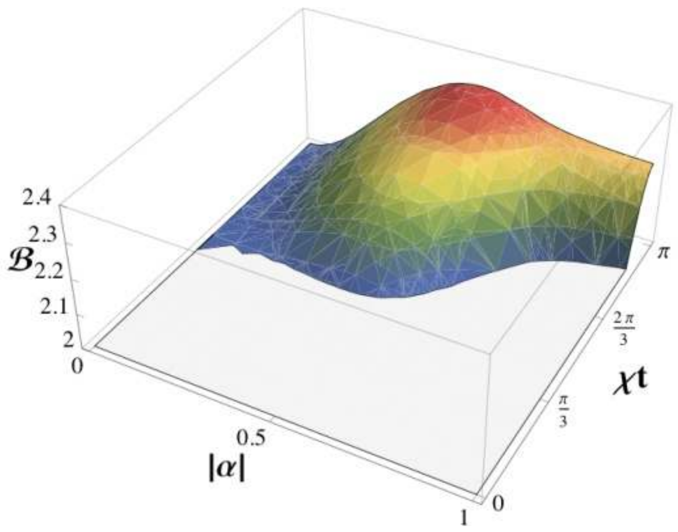

Figure 12: Quantum nonlocality for entangled states generated via matter-field interactions. The states are nonlocal when the Bell function B exceeds the local-realistic bound 2. In the figure, xt indicates the interaction time and alpha parameter determines the size of the entangled system. We are currently investigating the optimized time and alpha-parameter condition under various conditions

As indicated in our research plan, we will study Leggett-type inequalities using macroscopic entangled states to show violations of non-local realism in the macroscopic regime. We will also study possibility of efficient quantum teleportation and quantum information transfer using hybrid entangled states. Efficiencies of quantum information transfer will be analyzed in terms of fidelity and distance measures between input and output states. Based on the study of quantum information transfer between the light and matter, we will carry on the final research on the possibility of quantum information processing using hybrid systems of the BEC and optical systems.

C.2. List of publications during the first phase

C.2.1 SCI Journals

Juhee Yang, Sang-Bum Lee, Songky Moon, Soo-Young Lee, Sang Wook Kim, Truong Thi Anh Dao, Jai-Hyung Lee, and Kyungwon An, "Pump-induced dynamical tunneling in a deformed microcavity laser", Physical Review Letters **104**, 243601 (2010).

Wontaek Seo, Hyun-Gue Hong, Moonjoo Lee, Younghoon Song, Young-Tak Chough, Wonshik Choi, C. Fang-Yen, R. R. Dasari, M. S. Feld, Jai-Hyung Lee, and Kyungwon An, "Realization of a bipolar atomic Solc filter in the cavity-QED microlaser", Physical Review A **81**, 053824 (2010).

Sungsam Kang, Youngwoon Choi, Sooin Lim, Wookrae Kim, Jung-Ryul Kim, Jai-Hyung Lee, and Kyungwon An, "Continuous control of the coupling constant in an atom-cavity system by using elliptic polarization and magnetic sublevels", Optics Express **18**, 9286 (2010).

Youngwoon Choi, Sungsam Kang, Sooin Lim, Wookrae Kim, Jung-Ryul Kim, Jai-Hyung Lee, and Kyungwon An, "Quasieigenstate Coalescence in an Atom-Cavity Quantum Composite", Physical Review Letters **104**, 153601 (2010).

Hyun-Gue Hong, Hyunchul Nha, Jai-Hyung Lee, and Kyungwon An, "Rigorous criterion for characterizing correlated multiphoton emissions", Optics Express **18**, 7092 (2010).

Sang-Bum Lee, Juhee Yang, Songky Moon, Soo-Young Lee, Jungbo Shim, Sang-Wook Kim, Jai-Hyung Lee, and Kyungwon An, "Observation of an exceptional point in a chaotic optical microcavity", Physical Review Letters **103**, 134101 (2009).

Hyun-Gue Hong, Wontaek Seo, Moonjoo Lee, Younghoon Song, Young-Tak Chough, Jai-Hyung Lee, and Kyungwon An, "Atomic Solc filter: multi- resonant photoemission via periodic poling of atom-cavity coupling constant", Optics Express **17**, 15455 (2009).

Sang-Bum Lee, Juhee Yang, Songky Moon, Soo-Young Lee, Jeong-Bo Shim, Sang Wook Kim, Jai-Hyung Lee, and Kyungwon An, "Quasi-Eigenstate Evolution in Open Chaotic Billiards", Physical Review A **80**, 011802(R) (2009).

Hyun-Gue Hong, Wontaek Seo, Moonjoo Lee, Younghoon Song, Wonshik Choi, Christopher Fang-Yen, Ramachandra R. Dasari, Michael S. Feld, Jai-Hyung Lee and Kyungwon An, "Effects of coupled bichromatic atom-cavity interaction in the cavity-QED microlaser", Physical Review A **79**, 033816 (2009).

Chang-Woo Lee and Hyunseok Jeong, "Effects of squeezing on quantum nonlocality of superpositions of coherent states", Physical Review A **80**, 052105 (2009).

Mauro Paternostro and Hyunseok Jeong, "Testing nonlocal realism with entangled coherent states", Physical Review A **81**, 032115 (2010).

Dominic W. Berry, Hyunseok Jeong, Magdalena Stobinska, and Timothy C. Ralph, “Fair-sampling assumption is not necessary for testing local realism”, Physical Review A **81**, 012109 (2010).

Seung-Woo Lee, Hyunseok Jeong, and Dieter Jaksch, "Witnessing entanglement in phase space using inefficient detectors", Physical Review A **81**, 012302 (2010).

A. Zavatta, V. Parigi, M. S. Kim, H. Jeong, and M. Bellini, “Experimental demonstration of the bosonic commutation relation via superpositions of quantum operations on thermal light fields”, Physical Review Letters **103**, 140406 (2009).

Hyunseok Jeong, Mauro Paternostro, and Timothy C. Ralph, “Failure of local realism revealed by extremely coarse-grained measurements”, Physical Review Letters **102**, 060403 (2009).

Seung-Woo Lee, Hyunseok Jeong, and Dieter Jaksch, “Testing quantum non-locality by generalized quasiprobability functions”, Physical Review A **80**, 022104 (2009).

G. Mc Keown, F.L. Semiao, H. Jeong and M. Paternostro, "Genuine multipartite nonlocality of entangled thermal states", Phys. Rev. A **82**, 022315 (2010).

M. Paternostro, H. Jeong, and T. C. Ralph, “Violations of Bell's inequality for Gaussian states with homodyne detection and nonlinear interactions”, Phys. Rev. A **79**, 012101 (2009).

Yong-il Shin, “Surprise in the strong regime”, Nature **463**, 1029 (2010).

Christian Sanner, Edward J. Su, Aviv Keshet, Ralf Gommers, Yong-il Shin, Wujie Huang, and Wolfgang Ketterle, “Suppression of Density Fluctuations in a Quantum Degenerate Fermi Gas”, Physical Review Letters **105**, 040402 (2010).

Yong-il Shin, “RF Spectroscopy of a Resonantly-interacting Fermi Gas”, Journal of the Korean Physical Society **57**, 395 (2010).

W. Ketterle, Y. Shin, A. Schirotzek, C. H. Schunck, “Superfluidity in a gas of strongly interacting fermions”, Journal of Physics: Condensed Matter **21**, 164206 (2009).

C.2.2. Invited talks at international conferences

Kyungwon An, "High efficient optical pumping based on dynamical tunneling in a deformed microcavity laser", 12th International Conference on Transparent Optical Networks (Munich, Germany, 27 June - 1 July 2010).

Kyungwon An, "Direct observation of pump-induced dynamical tunneling in a deformed microcavity laser", Optical Microcavities: Quantum Chaos in Open Systems Meets Optical Resonators, 3rd Asian-German Workshop (Dresden, Germany, 17-21 May 2010).

Kyungwon An, "Eigenmode evolution in an atom-cavity system", ICTON 2009, Paper No. Tu.D4.1 (Ponta Delgada, Portugal, 28 June - 2 July, 2009).

Kyungwon An, "Exceptional point in an atom-cavity composite", Feld-Fest (MIT, Cambridge, U.S.A., 27 June 2009).

Kyungwon An, "Turnstile transport and Chaos-Assisted Tunneling in deformed microcavities", SPIE Photonics West 2009, Paper No. 7194-32 (San Jose, U.S.A., 24-29 January 2009).

Yong-il Shin, "Determination of the fermion pair size and the superfluid gap in a unitary Fermi gas", The 16th International Symposium on Laser Spectroscopy (Daejeon, Korea, 11-12 November 2009).

H. Jeong, "Macroscopic Entanglement and Its Usefulness in Quantum Information Science", 5th Asia Pacific Conference on Quantum Information Science(5'APCQIS) (Shanxi Taiyuan, China, August 22~24, 2010).

H. Jeong, "Schrödinger cat states of light and quantum control", The 6th International Conference on Advanced Materials and Devices (ICAMD 2009) (Jeju, Korea, December 10~11, 2009).

H. Jeong, "Testing quantum mechanics using Gaussian and non-Gaussian light fields," SPIE Photonics West (San Jose, USA, January 28~29, 2009).

C.2.3 Contributed presentation at international conferences (selected list)

Wookrae Kim, Youngwoon Choi, Sungsam Kang, Jung-ryul Kim, Sooin Lim, Jai-Hyung Lee, and Kyungwon An, "Tunneling effect in the resonance fluorescence spectrum of a single atom localized in an optical-lattice-like potential in the Lamb-Dicke regime", International Conference on Quantum Information Processing and Communication (QIPC), Paper No. Th33 (poster presentation) (Rome, Italy, 21-25 September 2009).

Sungsam Kang, Youngwoon Choi, Sooin Lim, Wookrae Kim, Jai-Hyung Lee, and Kyungwon An, "Observation of the exceptional point in an atom-cavity system", International Conference on Quantum Information Processing and Communication (QIPC), Paper No. Th32 (poster presentation) (Rome, Italy, 21-25 September 2009).

Hyun-Gue Hong, Hyunchul Nha, Jai-Hyung Lee, and Kyungwon An, "A proposed optimal measurement for probing correlated multiphoton emission induced by the anharmonic ladder of the Jaynes-Cummings system", International Conference on Quantum Information Processing and Communication (QIPC), Paper No. Mo41 (poster presentation) (Rome, Italy, 21-25 September 2009).

Sungsam Kang, Sooin Lim, Myoung Kyu Hwang, Wookrae Kim, Jungryul Kim, Jai-Hyung Lee, and Kyungwon An, "On-demand generation of single photons with a coupled atom cavity system", International Symposium on Physics of Quantum Technology (ISPQT), Paper No. 7W-73 (poster presentation) (Tokyo, Japan, 6-9 April 2010).

Wookrae Kim, Changwon Park, Jung-ryul Kim, Sungsam Kang, Sooin Lim, Yea-Lee Lee, Jaewan Kim, Jisoon Ihm, Jai-Hyung Lee and Kyungwon An, "Trapping a single atom in an optical lattice-like potential in a strong Lamb-Dicke regime", International Symposium on Physics of Quantum Technology (ISPQT), Paper No. 7W-72 (poster presentation) (Tokyo, Japan, 6-9 April 2010).

Younghoon Shin, Hojeong Kwak, Sang-Bum Lee, Juhee Yang, Songky Moon, Soo-Young Lee, Sang Wook Kim, Jai-Hyung Lee, and Kyungwon An, "Resonance mode properties in a liquid-filled ultrasonic cavity", OPTIMI10, Paper No. 11 (poster presentation) (Dresden, Germany, 17 - 21 May 2010).

Songky Moon, Juhee Yang, Sang-Bum Lee, Younghoon Shin, Hojeong Kwak, KunJoong Park, Ho-Young Kim, Jai-Hyung Lee, Soo-Young Lee, and Kyungwon An, "Surface profile of a chaotic microcavity and Niels Bohr's unknown insight in hydrodynamics", OPTIMI10, Paper No. 9 (poster presentation) (Dresden, Germany, May 17 - 21 2010).

Hojeong Kwak, Younghoon Shin, Sang-Bum Lee, Juhee Yang, Songky Moon, Soo-Young Lee, Sang Wook Kim, Jai-Hyung Lee, and Kyungwon An, "Resonance mode calculations in an acoustic cavity using the boundary element method", ICTON 2010, Paper No. Mo.P.12 (poster presentation) (Munich, Germany, 27 June - 1 July 2010).

Juhee Yang, Sang-Bum Lee, Songky Moon, Soo-Young Lee, Jeong-Bo Shim, Sang Wook Kim, Jai-Hyung Lee, and Kyungwon An, "Resonant Pump Transmission in a Strongly Deformed Microcavity", ICTON 2010, Paper No. Mo.P.14 (poster presentation) (Munich, Germany, 27 June - 1 July 2010).

Jung-ryul Kim, Wookrae Kim, Changwon Park, Sungsam Kang, Sooin Lim, Jaewan Kim, Jisoon Ihm, and Kyungwon An, "Tunneling effect observed in the resonance fluorescence spectrum of a single atom in a Lamb-Dicke regime", 22nd International Conference on Atomic Physics (ICAP 2010), Paper No. Mo101 (poster presentation) (Cairns, Australia, 25-30 July 2010).

Sooin Lim, Youngwoon Choi, Sungsam Kang, Wookrae Kim, Jung-ryul Kim, Jai-Hyung Lee, and Kyungwon An, "Quasieigenstate Coalescence at the Exceptional Point in a Coupled Atom-Cavity System", 22nd International Conference on Atomic Physics (ICAP 2010), Paper No. Tu137 (poster presentation) (Cairns, Australia, 25-30 July 2010).

Younghoon Song, Wontaek Seo, Hyun-Gue Hong, Moonjoo Lee, Jai-Hyung Lee, and Kyungwon An, “Enhancing nonclassicality of the photon statistics in the cavity-QED microlaser”, EMALI Conference 2010, Paper No. P61 (poster presentation) (BARCELONA, Spain, 23-25 September 2010).

Myoung Kyu Hwang, Sooin Lim, Sungsam Kang, Wookrae Kim, Jung-ryul Kim, Jai-Hyung Lee, and Kyungwon An, “Rapid Single-Photon Generation with a Coupled Atom-Cavity System”, EMALI Conference 2010, Paper No. P32 (poster presentation) (BARCELONA, Spain, 23-25 September 2010).

Chang-Woo Lee, and Hyunseok Jeong, “Effects of squeezing on quantum nonlocality of superpositions of coherent states”, Asian Conference on Quantum Information Science (AQIS), Paper No. 176 (poster presentation) (Nanjing, China, 26-29 August 2010).

Kimin Park, and Hyunseok Jeong, “Comparison of the degrees of entanglement for polarization-entangled two photon states and entangled coherent states”, Asian Conference on Quantum Information Science (AQIS), Paper No. 184 (poster presentation) (Nanjing, China, 26-29 August 2010).

Chang-Woo Lee, and Hyunseok Jeong, “Effects of squeezing on Bell violations with superpositions of coherent states”, International Symposium on Physics of Quantum Technology (ISPQT), Paper No. 7w-71 (poster presentation) (Tokyo, Japan, 6-9 April 2010).

Kimin Park, and Hyunseok Jeong, “Decoherence properties of entangled photon pair and entangled coherent states”, International Symposium on Physics of Quantum Technology (ISPQT), Paper No. 7w-70 (poster presentation) (Tokyo, Japan, 6-9 April 2010).

Chang-Woo Lee, and Hyunseok Jeong, “Testing non-local realism through Leggett inequality test with entangled coherent states”, International Conference on Quantum Communication, Measurement and Computation (QCMC), Paper No. P1-7 (poster presentation) (Brisbane, Australia, 19-23 July 2010).

Kimin Park, and Hyunseok Jeong, “Decoherence properties of polarization-entangled photon pair andentangled coherent states”, International Conference on Quantum Communication, Measurement and Computation (QCMC), Paper No. P1-6 (poster presentation) (Brisbane, Australia, 19-23 July 2010).

Part D. Representative Papers of the Research Team

D1. Korean Participant(s)

No.	Name	Publication year	Title	Role(check)		Journal Name	SCI (O/X)	SCOPUS (O/X)
				First Author	Corresponding Author			
D1.1	An, Kyungwon	2010.	Quasieigenstate Coalescence in an Atom-Cavity Quantum Composite		√	Physical Review Letters	○	○

D2. Foreign Participant(s)

No.	Name	Publication year	Title	Role(check)		Journal Name	SCI (O/X)	SCOPUS (O/X)
				First Author	Correspon ding Author			
D2.1	신용일	2010.	Surprise in the strong regim	√	√	Nature	○	○

간지

〈 Representative Papers (Korean Participant(s)) 〉

Quasieigenstate Coalescence in an Atom-Cavity Quantum Composite

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We report the first direct observation of an exceptional point (EP) in an open quantum composite of a single atom and a high-Q cavity mode. The atom-cavity coupling constant was made a continuous variable by utilizing the multisublevel nature of a single rubidium atom when it is optimally coupled to the cavity mode. The spectroscopic properties of quasieigenstates of the atom-cavity composite were experimentally investigated near the EP. Branch-point singularity of quasieigenenergies was observed and its 4π symmetry was demonstrated. Consequently, the cavity transmission at the quasieigenstate was observed to exhibit a critical behavior at the EP.

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Quantitative understanding of open quantum composites is important for better design and operation of nano- and microscale devices. Open quantum composites can be described by non-Hermitian Hamiltonian. If a system is described by a non-Hermitian Hamiltonian with adjustable system parameters, its energy eigenstates can coalesce to a single self-orthogonal state for a particular set of the system parameters [1,2]. When its quasieigenvalues are presented in the parameter space, this particular set of the parameters represents an exceptional point (EP), at which eigenstate exchange and nontrivial geometric phase under cyclic parameter variation occur [3]. Since any physical system has energy dissipation and is thus describable by a non-Hermitian Hamiltonian, the occurrence of EP is generic. For this reason, EP has been an active subject of theoretical studies in many different systems [4–7] including laser-induced degenerate states in autoionization [4] and divergent spontaneous emission rate at EP [8]. Its experimental observations have been recently reported in classical systems of interacting cavity modes [9–12].

One of the representative systems of open quantum composites is the Jaynes-Cummings system (JCS), a single two-level atom coupled to a single high-Q cavity mode, with atomic and cavity damping. The JCS has drawn much attention due to its fundamental importance and applicability in quantum information. Recently realized are single-atom lasers [13,14], single photon on demand [15,16], multiphoton gateways [17], direct observation of photons [18], single-photon phase [19], etc., in the context of cavity quantum electrodynamics (QED) [20]. The JCS is also realized in circuit QED systems [21] and quantum dots in microdisks [22,23]. However, its relevance to the study of EP has little been recognized, but we note the open JCS has a potential to be one of the ideal systems to study EP experimentally. It is because the coupling constant between the atom and the cavity is analytically well known [20], which is not the case in general in other systems, and also because very high-resolution studies are possible owing to well-established atomic physics and quantum optics techniques. Moreover, the atom-cavity system is truly a quantum system, fundamentally different from the previously studied classical systems emulating a quantum one.

For the study of EP, we need at least two adjustable parameters controlling the interaction Hamiltonian [6,10]. One available parameter is the atom-cavity detuning, which is completely adjustable. Another relevant parameter is the atom-cavity coupling constant. Although the spectroscopic properties of the atom-cavity system were intensively studied with single atoms [24,25], there has been no good way to vary the coupling constant continuously for a single two-level atom. As a result, an experimental study of EP with a single-atom JCS, despite its conceptual simplicity, has remained no less than elusive.

In this Letter, we report the first direct observation of an EP, namely, the coalescence of two quasieigenstates into a single state, in a quantum composite of a single atom and a high-Q cavity mode. For this, we implemented a continuously changeable atom-cavity coupling constant by utilizing the multisublevel nature of a single rubidium atom. The spectroscopic properties of the quasieigenstates are then investigated across the EP and the quasieigenvalues around the EP are shown to exhibit a singular topology. Consequently, a discontinuous slope change in the quasieigenstate cavity transmission is observed across the EP.

Our scheme of making a continuously adjustable atom-cavity coupling constant is based on the multisublevel nature of the so-called *degenerate* two-level atom with each level consisting of degenerate magnetic sublevels. The induced dipole moment of the degenerate two-level atom has a strong dependence on the initial and final magnetic sublevels of the transition. If the cavity field is elliptically polarized, all magnetic sublevels participate in the interaction and thus the coupling constant between the atom and the field would be averaged over all possible transitions. It has been semiclassically proven that a degenerate two-level atom interacting with an elliptically polarized classical field in a free space behaves as if a nondegenerate two-level atom in the steady state with an effective transition matrix element [26,27]. We have recently extended the theory to an atom-cavity composite in a fully quantum mechanical way [28]. It has been shown that under weak excitation a degenerate two-level atom interacts with the cavity mode in the steady state as if a nondegenerate two-level atom with an effective atom-cavity coupling constant given by

$$g(\theta) = g_0\sqrt{\sum_{i=1}^{2F+1} \lambda_i^2(\theta)\pi_i(\theta)}, \tag{1}$$

for a hyperfine transition $F(\text{ground}) \rightarrow F'(\text{excited}) = F + 1$. Here g_0 is the maximum coupling constant determined by the strongest cycling transition and θ is the elliptic angle of the cavity-field polarization. The parameters π_i and λ_i are the relative population of the ith ground sublevel and the normalized transition strength for the ith π transition [27,28], respectively, in the Morris-Shore natural basis [26], which is transformed from the usual atom-field basis. Since λ_i and π_i are algebraic functions of the elliptical angle of the cavity field alone [28], g can be controlled entirely by the ellipticity of a driving laser.

Under a weak excitation, the atom-cavity system is well described by one-quantum atom-field basis $|e, 0\rangle$ and $|g, 1\rangle$ with excited (ground) state of atom with 0(1) photon [29], then H', the interaction Hamiltonian with atomic and cavity decays, is represented by the following non-Hermitian matrix [30]:

$$H' = \hbar\begin{bmatrix} \omega_a - i\gamma_a & g \\ g & \omega_c - i\gamma_c \end{bmatrix}, \tag{2}$$

where $\gamma_a(\gamma_c)$ and $\omega_a(\omega_c)$ are the decay rate and the resonance frequency of the atom (cavity). Diagonalizing the matrix gives two quasieigenstates $|\pm\rangle$ satisfying biorthogonality and corresponding complex quasieigenenergies $E_\pm$ [29]. When $g = \gamma_- \equiv |\gamma_c - \gamma_a|/2$ and $\Delta_{ca} \equiv \omega_c - \omega_a = 0$, the states $|\pm\rangle$ coalesce to a single self-biorthogonal state $|\text{EP}\rangle = (|e, 0\rangle - i|g, 1\rangle)/\sqrt{2}$ with $E_{\text{EP}} = \omega_a - i(\gamma_c + \gamma_a)/2$, corresponding to an exceptional point in (Δ_{ca}, g) space.

Our experimental setup, similar to that of Ref. [31] is depicted in Fig. 1(a). We use a TEM_{11} cavity mode with a decay rate of $\gamma_c/2\pi = 21.0$ MHz, corresponding to a finesse of about 2×10^4, for which mirror birefringence has negligible effects [32]. The cavity is tuned to the atomic transition $5S_{1/2}$, $F = 3 \leftrightarrow 5P_{3/2}$, $F' = 4$ with a radiative decay rate $\gamma_a/2\pi = 3.0$ MHz, and thus we have $\gamma_-/2\pi = 9.0$ MHz. The coupling constant g can be varied from a maximum of $g_0/2\pi = 11.1$ MHz when circular polarization is used to a minimum of $0.73g_0$ when linear polarization is used [29], so the EP condition, $g = \gamma_-$ is well covered. The observed g as a function of θ is presented in Fig. 1(d) and more details are explained in Ref. [29].

In our experiment, about 10^4 ^{85}Rb atoms at a temperature of 20 μK after sub-Doppler cooling are dropped from a magneto-optical trap (MOT) positioned 6 mm above the cavity mode. A probe laser is locked to the atomic transition line (ω_a) and then shifted by Δ_{ca} with an acousto-optic modulator. The cavity is locked to this shifted probe at $\omega_a + \Delta_{ca}$. Frequency modulation lock technique is used for both locks. When atoms go through the cavity, the cavity lock is removed and the probe laser shift is changed to Δ_{pa}, defined below, for transmission measurement for 40 ms. The cavity transmission is continuously monitored with an avalanche photodiode (APD) for the cavity stabilization and simultaneously with a single-photon-counting module (SPCM) for recording the cavity transmission when the falling atoms individually interact with the cavity mode while traversing it. For weak excitation of the atom-cavity system, the probe power is kept at 1 nW, making the mean photon number for the empty cavity 0.027, much smaller than the saturation photon number ($\sim$0.04) of the system.

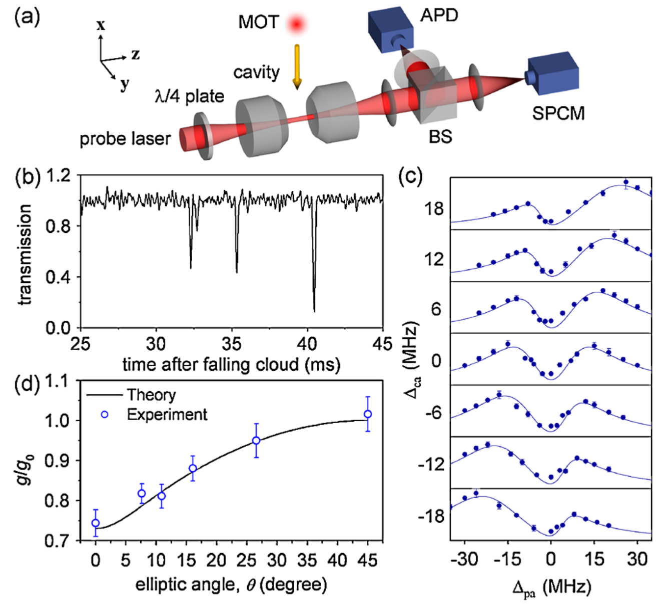

FIG. 1 (color online). (a) Experimental schematic. The cavity is composed of two supermirrors with a cavity length of 155 μm. Probe polarization is controlled by a quarter wave plate at the input port of the cavity. (b) Typical time trace of cavity transmission when $\Delta_{pa} = 0$ and $\Delta_{ca} = 0$. Each peak is a response of a transiting single atom. (c) Transmission spectra for various Δ_{ca}, measured with a TEM_{11} mode and circular polarization. Solid lines are predictions, not fits, by the full-quantum theory of Refs. [28,30] for our experimental parameters. (d) Measured g as a function of the elliptical angle θ.

Per each drop of atoms, only a few atoms traverse the cavity mode and their individual transit events are well resolved in the cavity transmission as shown in Fig. 1(b). The transit time is about 150 μs, so much longer than atomic and cavity decay times that a steady-state transmission is quickly established during the transit. The drop is repeated 100 times for any given set of parameters. We then take the average of the top-five transit events that give the largest changes in transmission, regarding them as the events made by optimally coupled atoms whose trajectories go through antinodes of the mode. By recording the cavity transmission by the optimally coupled atoms for a fixed g but for various Δ_{ca} as a function of probe-atom detuning $\Delta_{pa} \equiv \omega_p - \omega_a$ with ω_p the probe laser frequency, we obtain the excitation spectrum of the atom-cavity composite as shown in Fig. 1(c). A symmetric two-peak line shape observed when $\Delta_{ca} = 0$ corresponds to the well-known normal-mode splitting of the atom-cavity system. By fitting each spectrum with the full-quantum-mechanical theory [28,30], we then obtain the real (resonance frequency) and the imaginary (decay rate) parts of the quasieigenenergies.

Figure 2 shows the observed behavior of the complex eigenenergies when Δ_{ca} is varied, for various coupling constant g. When the probe laser is circularly polarized ($\theta = \pi/4$) in Fig. 2(a), we have $g/\gamma_- = 1.23 \pm 0.04$, satisfying the strong coupling condition. For $\Delta_{ca} = 0$ the quasieigenstates are given by $|\pm\rangle \simeq (|e, 0\rangle \pm |g, 1\rangle)/\sqrt{2}$ in the limit of $g/\gamma_- \gg 1$. As Δ_{ca} is varied, the real part (resonance frequency) exhibits avoided crossing (AC) and the imaginary part (decay rate or linewidth) shows diabatic crossing (DC) or simple crossing. Equivalently, two quasieigenstates interchange their linewidths upon AC.

Trajectories of the quasieigenenergies in a complex plane provides a more comprehensive view as in Fig. 3(a). Compared to a pointlike atom state and a horizontal-line cavity state in Fig. 3(d) in the case of no coupling, the $|+\rangle$ state is changed gradually from an atomlike state (A) to a cavitylike state (B) due to the strong interaction between the atom and the cavity mode. The $|-\rangle$ state starting from the upper left region exhibits the opposite, gradually transforming from an initial cavitylike state to a final atomlike state.

On the other hand, in Fig. 2(c), the probe laser is linearly polarized ($\theta = 0$), and the coupling constant is given by $g/\gamma_- = 0.90 \pm 0.03$, corresponding to a weak coupling regime. We now observe DC of the real part and AC of the imaginary part. In the complex plane of Fig. 3(c), the $|+\rangle$ state starting from the lower central region (H) loops almost back to the starting position while the $|-\rangle$ state starting from the upper left region (D) goes to the right as Δ_{ca} is increased. In this case the weak atom-cavity interaction cannot convert each state to the other although it makes their trajectories deviated from those in Fig. 3(d).

For realizing the EP condition, we control the polarization of the probe laser with an elliptical angle of $\theta = 10.9°$ in Fig. 2(b). The resulting coupling constant is $g/\gamma_- = 1.01 \pm 0.04$, satisfying the EP condition within experimental uncertainty. The real and the imaginary parts show simultaneous crossing, which is the result of two quasieigenstates $|\pm\rangle$ coalescing to a single state, $|\mathrm{EP}\rangle$. This behavior is also clearly seen in Fig. 3(b), where two trajectories of the complex eigenenergies are severely bent and joined together at a single point within the experimental uncertainty.

One of the consequences of this quantum-state coalescence is that the quasieigenenergies presented in the (Δ_{ca}, g) parameter space exhibit a branch-point singularity at the EP [12]. As a result, a 2π rotation around the EP in the parameter space results in interchanged states. A 4π rotation is needed in order to recover the original state except for a geometric phase of π [3]. Such topological properties are revealed under a cyclic parameter variation of (Δ_{ca}, g/γ_-): $(-18\ \mathrm{MHz}, 1.23) \rightarrow (+18\ \mathrm{MHz}, 1.23) \rightarrow (+18\ \mathrm{MHz}, 0.90) \rightarrow (-18\ \mathrm{MHz}, 0.90) \rightarrow (-18\ \mathrm{MHz}, 1.23)$. Suppose we start from $|+\rangle$ state in Fig. 2(a) and follow this

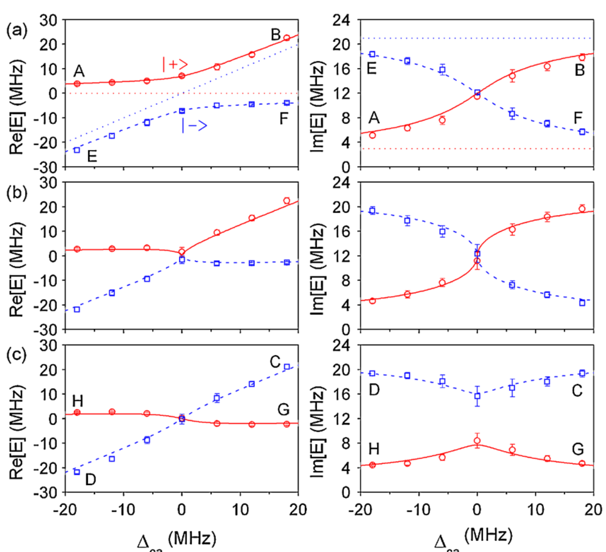

FIG. 2 (color online). Real and imaginary parts of the observed quasieigenenergies. (a) $g/\gamma_- = 1.23 \pm 0.04$ (strong coupling), (b) $g/\gamma_- = 1.01 \pm 0.04$ (EP condition), and (c) $g/\gamma_- = 0.90 \pm 0.03$ (weak coupling). Solid and dashed lines are theoretical predictions, not fits, for the experiment. Dotted lines in (a) represent the case of no coupling.

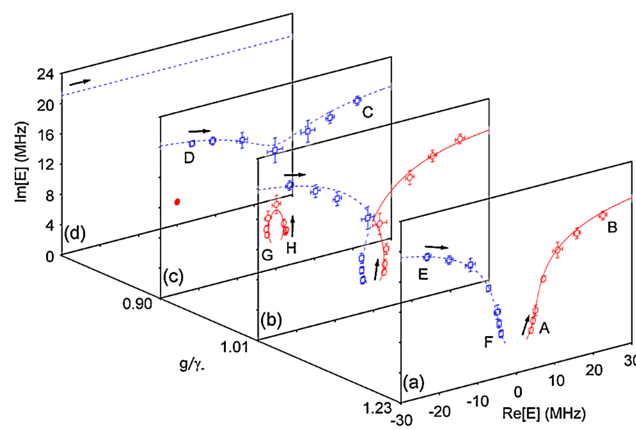

FIG. 3 (color online). Complex eigenenergy trajectories in the strong coupling (a) and in the weak coupling regimes (c). The arrows indicate the direction of progression of the eigenenergies when Δ_{ca} is scanned from -18 to $+18$ MHz. (b) Under the EP condition, the two trajectories are joined at one point, indicating coalescence of two eigenstates into one. (d) The case of no coupling.

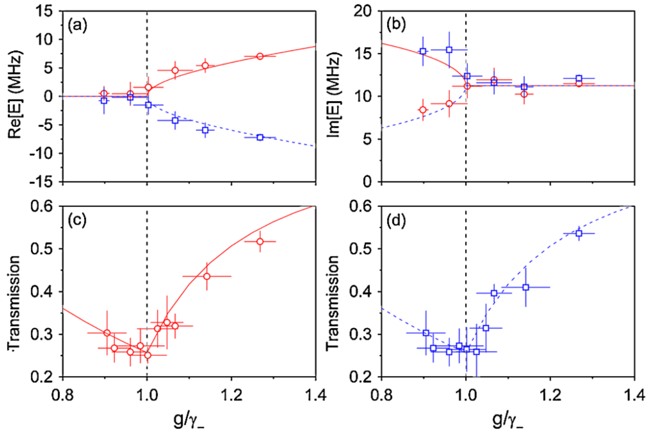

FIG. 4 (color online). Critical cavity transmission. (a) Real and (b) imaginary parts of the eigenenergies when $\Delta_{ca} = 0$. (c) Cavity transmission at the resonance of $|+\rangle$ eigenstate and (d) that of $|-\rangle$ state. Solid and dashed lines in (a) and (b) are theoretical predictions and those in (c) and (d) are numerical fits by the steady-state solution of the master equation [29] with the intracavity mean photon number $\bar{n}$ as a fitting parameter. The result is $\bar{n} = 0.027 \pm 0.001$. Horizontal error bars are mostly due to the experimental uncertainty in γ_c measurement. Vertical error bars indicate the uncertainty in the cavity transmission measurement.

cyclic variation, then we end up with $|-\rangle$ state. In the complex plane of Fig. 3 under this cyclic variation the state moves from points A to E via points B, C, and D. One more looping in the parameter space is needed in order to regain the original state, corresponding to a trace $E \rightarrow F \rightarrow G \rightarrow H \rightarrow A$.

Finally, we show the transmission of the atom-cavity composite exhibits a critical behavior at the EP when a quasieigenstate is excited while varying g across the EP at zero atom-cavity detuning, $\Delta_{ca} = 0$. The real and the imaginary parts of the quasieigenvalues observed under this condition are presented in Figs. 4(a) and 4(b), respectively. We measured the cavity transmission of a weak probe laser whose frequency is set at the eigenfrequency of one of the quasieigenstates. The probe intensity was fixed under the weak excitation condition. The result, shown in Figs. 4(c) and 4(d) as a function of g, clearly shows a critical behavior at the EP, namely, a discontinuous slope change as well as a minimum at the EP. Both of the left slope $T'_<$ and the right slope $T'_>$ at the EP can be calculated as simple algebraic functions of γ_c and γ_a [29]. A minimum exists at the EP only when $\gamma_c > 3\gamma_a$, corresponding to our case ($\gamma_c \simeq 7\gamma_a$).

In conclusion, we have observed an EP in an open quantum composite of a single-atom and a single-cavity mode, and consequently, the critical quasieigenstate cavity transmission. This observation was made possible by making the atom-cavity coupling constant continuously variable. As a future study, a homodyne technique can be used on the cavity transmission in order to measure the π phase shift in a quasieigenstate after a 4π rotation around the EP. Although eigenstates coalesce at EP, it is pointed out there should exist two generalized eigenstates in general in nonstationary states [33]. The second-order correlation function study at the EP would shed light on their existence. It would be also interesting to study EPs in other practical quantum composites such as polariton and polaron systems.

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[1] T. Kato, *Perturbation Theory for Linear Operators* (Springer, New York, 1966).
[2] W. D. Heiss and W.-H. Steeb, J. Math. Phys. (N.Y.) **32**, 3003 (1991).
[3] W. D. Heiss, Eur. Phys. J. D **7**, 1 (1999).
[4] O. Latinne *et al.*, Phys. Rev. Lett. **74**, 46 (1995).
[5] P. Cejnar, S. Heinze, and M. Macek, Phys. Rev. Lett. **99**, 100601 (2007).
[6] H. Cartarius, J. Main, and G. Wunner, Phys. Rev. Lett. **99**, 173003 (2007).
[7] R. Lefebvre *et al.*, Phys. Rev. Lett. **103**, 123003 (2009).
[8] S.-Y. Lee *et al.*, Phys. Rev. A **78**, 015805 (2008).
[9] M. Philipp *et al.*, Phys. Rev. E **62**, 1922 (2000).
[10] C. Dembowski *et al.*, Phys. Rev. Lett. **86**, 787 (2001).
[11] C. Dembowski *et al.*, Phys. Rev. Lett. **90**, 034101 (2003).
[12] S.-B. Lee *et al.*, Phys. Rev. Lett. **103**, 134101 (2009).
[13] K. An *et al.*, Phys. Rev. Lett. **73**, 3375 (1994).
[14] J. McKeever *et al.*, Nature (London) **425**, 268 (2003).
[15] A. Kuhn, M. Hennrich, and G. Rempe, Phys. Rev. Lett. **89**, 067901 (2002).
[16] J. McKeever *et al.*, Science **303**, 1992 (2004).
[17] A. Kubanek *et al.*, Phys. Rev. Lett. **101**, 203602 (2008).
[18] S. Gelyzes *et al.*, Nature (London) **446**, 297 (2007).
[19] H. P. Specht *et al.*, Nat. Photon. **3**, 469 (2009).
[20] *Cavity Quantum Elecrodynamics*, edited by P. R. Berman (Academic Press, Boston, 1994).
[21] A. Wallraff *et al.*, Nature (London) **431**, 162 (2004).
[22] J. P. Reithmaier *et al.*, Nature (London) **432**, 197 (2004).
[23] T. Yoshie *et al.*, Nature (London) **432**, 200 (2004).
[24] A. Boca *et al.*, Phys. Rev. Lett. **93**, 233603 (2004).
[25] P. Maunz *et al.*, Phys. Rev. Lett. **94**, 033002 (2005).
[26] J. R. Morris and B. W. Shore, Phys. Rev. A **27**, 906 (1983).
[27] A. V. Taichenachev *et al.*, Phys. Rev. A **69**, 033410 (2004).
[28] S. Kang *et al.*, arXiv:0906.3584.
[29] See supplementary material at http://link.aps.org/supplemental/10.1103/PhysRevLett.104.153601 for more theoretical and experimental details.
[30] H. J. Carmichael, *Statistical Methods in Quantum Optics 2* (Springer, New York, 2008).
[31] C. J. Hood *et al.*, Phys. Rev. Lett. **80**, 4157 (1998).
[32] D. Jacob *et al.*, Opt. Lett. **20**, 671 (1995).
[33] A. P. Seyranian, O. N. Kirillov, and A. A. Mailybaev, J. Phys. A **38**, 1723 (2005).

간지

〈 Representative Papers (Foreign Participant(s)) 〉

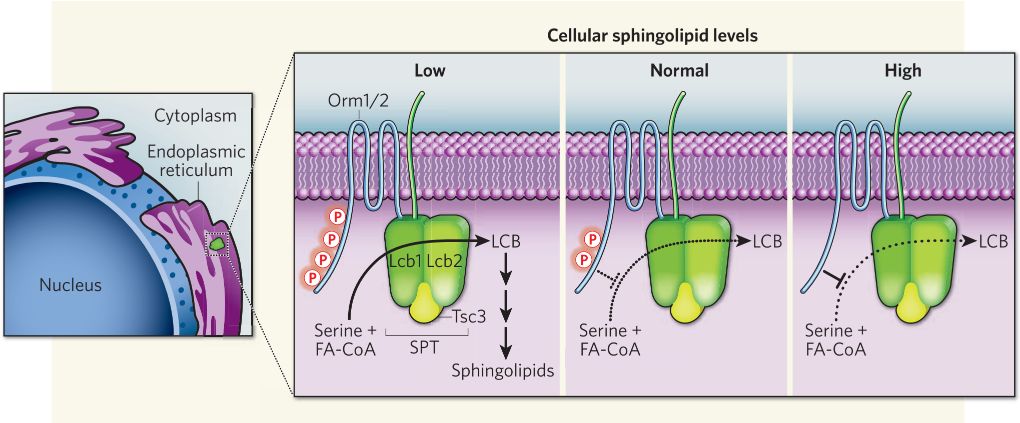

Figure 1 | Orm proteins control sphingolipid homeostasis in the endoplasmic reticulum. Sphingolipid synthesis starts with the formation of a long-chain base (LCB) from serine and fatty acyl-CoA (FA-CoA) in a reaction catalysed by serine palmitoyltransferase (SPT) on the cytoplasmic side of the endoplasmic reticulum. SPT subunits Lcb1, Lcb2 and Tsc3 form a complex with the proteins Orm1 and Orm2. When cellular sphingolipid levels are plentiful, Orm proteins act as negative regulators of LCB synthesis. But when sphingolipids are in short supply, multi-site phosphorylation of Orm proteins gradually relieves their inhibitory activity, thereby restoring sphingolipid homeostasis. The identity of the intermediate in the sphingolipid synthetic pathway whose levels are sensed to control Orm phosphorylation is not known.

proteins are negative regulators of sphingolipid synthesis, and act directly on SPT.

But why would cells include negative regulators as core components of an essential enzyme complex? A notable clue came when Breslow *et al.* examined the sensitivity of Orm-deficient cells to the SPT inhibitor myriocin. Unexpectedly, removal of Orm1/2 did not confer any resistance to this drug. Moreover, normal cells maintained constant LCB levels at myriocin concentrations that effectively suppressed LCB accumulation in Orm-deficient cells. This observation implies that cells can generate a constant sphingolipid output in the face of increasing SPT inhibition by gradually relieving an Orm1/2-mediated brake on LCB synthesis.

Curiously, myriocin did not affect Orm1/2 expression or binding to Lcb1/2. So how is the Orm1/2-mediated brake on LCB synthesis removed? Breslow *et al.* convincingly show that the brake is operated by a phosphorylation-based feedback loop (Fig. 1). Myriocin induces a dose-dependent addition of phosphate groups to Orm1/2 proteins at several sites in their amino-terminal region[4]. Mutations of these phosphorylation sites reduce basal LCB levels and make cells highly sensitive to myriocin. These elegant experiments establish the mechanistic basis of a sphingolipid rheostat with a central role for Orm1/2 proteins as homeostatic regulators of SPT.

The control of Orm1/2 activity by multisite phosphorylation has a distinct advantage. Besides allowing cells to respond rapidly to undesirable fluctuations in sphingolipid levels, this arrangement may provide a graded mechanism for finely adjusting sphingolipid synthesis to match cellular needs. Importantly, such a device would ensure an adequate supply of complex sphingolipids, while minimizing the risk of accumulation of the toxic intermediates.

But there are still some outstanding questions. How do Orm proteins regulate SPT? Do they alter the catalytic activity of Lcb1/2, or do they modulate the enzyme's access to its substrates? Which kinase and phosphatase enzymes control Orm phosphorylation? And what is the identity of the sphingolipid intermediate whose levels are sensed to regulate Orm activity? Preliminary evidence[4] suggests that Orm phosphorylation is sensitive to fluctuations in ceramide levels. This raises the question of whether a recently identified ceramide sensor in the endoplasmic reticulum[7] is part of the mechanism by which Orm proteins control sphingolipid homeostasis.

Two recent studies[8,9] report that, in the absence of Orm proteins, the process of protein quality control at the endoplasmic reticulum is impaired. Together with the findings of Breslow *et al.*, these studies provide a fresh starting point for investigating how protein and lipid synthesis is coordinated during membrane biogenesis. Breslow and colleagues' work might also have clinical implications. Because one of the human *ORM* genes has recently been implicated in childhood asthma[10], the present study indicates that dysregulation of sphingolipid metabolism may contribute to the development of this disease. This hypothesis merits verification, because it holds the promise of new therapies. ■

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1. Hanada, K., Nishijima, M. & Akamatsu, Y. *J. Biol. Chem.* **265,** 22137–22142 (1990).
2. Zhang, X., Skrzypek, M. S., Lester, R. L. & Dickson, R. C. *Curr. Genet.* **40,** 221–233 (2001).
3. Hannun, Y. A. & Obeid, L. M. *J. Biol. Chem.* **277,** 25847–25850 (2002).
4. Breslow, D. K. *et al. Nature* **463,** 1048–1053 (2010).
5. Gable, K., Slife, H., Bacikova, D., Monaghan, E. & Dunn, T. M. *J. Biol. Chem.* **275,** 7597–7603 (2000).
6. Schuldiner, M. *et al. Cell* **123,** 507–519 (2005).
7. Vacaru, A. M. *et al. J. Cell Biol.* **185,** 1013–1027 (2009).
8. Han, S., Lone, M. A., Schneiter, R. & Chang, A. *Proc. Natl Acad. Sci. USA* (in the press).
9. Cantero-Recasens, G., Fandos, C., Rubio-Moscardo, F., Valverde, M. A. & Vicente, R. *Hum. Mol. Genet.* **19,** 111–121 (2010).
10. Moffatt, M. F. *et al. Nature* **448,** 470–473 (2007).

LOW-TEMPERATURE PHYSICS

Surprise in the strong regime

Yong-il Shin

The finding that the normal phase of an ultracold gas of fermionic atoms in the strongly interacting regime is close to a Fermi liquid isn't quite what theorists expected for these systems.

During the past decade, ultracold gases of fermions (particles with half-integer spin, such as electrons) gained renown as a tool for modelling the physics of strongly interacting many-body systems. In the vicinity of a Feshbach resonance, these systems can be conveniently controlled with a magnetic field to reach the unitary limit, the point at which the interactions between particles become strongest and the thermodynamic properties of the system become universal — that is, independent of the nature of the interactions[1]. As such, ultracold Fermi gases with tunable interactions allow us to probe the crossover from the Bardeen–Cooper–Schrieffer (BCS) superfluid state, which describes the frictionless flow of weakly interacting electron pairs in superconductors, to the Bose–Einstein condensate (BEC) superfluid state, which occurs in systems made of bosons (particles with whole-integer spin) such as helium-4 (ref. 2); the gas's weakly interacting fermions can be made to interact strongly and bind together into bosonic molecules that ultimately condense into a BEC. On page 1057 of this issue, Nascimbène *et al.*[3] provide insight into the strongly interacting, BCS–BEC crossover regime by devising an experiment that yields the equation of state for a unitary Fermi gas.

The equation of state of a physical system is a

50 & 100 YEARS AGO

50 YEARS AGO

In my opinion the trouble with African agriculture is not that information is not properly co-ordinated, but that the basic facts are simply not known. So little fundamental agricultural research has been done ... Even attempts at developments like the Groundnut Scheme ... seem less wasteful when it is realized that for every pound lost in this and in all agricultural schemes attempted in Africa since the War, much more than a hundred pounds has been spent in subsidizing British agriculture at home. More money will have to be spent on research in Africa. We need to have more and better research workers in the laboratories and in the field; I believe they will use the limited resources better than those who fritter away so much time and money attending international conferences and endless meetings of co-ordinating committees which lack the basic facts to co-ordinate. **Kenneth Mellanby**

From *Nature* 27 February 1960.

100 YEARS AGO

The Irish Fairy Book. By Alfred Perceval Graves — There is a greater demand for fairy books than there is for works on folklore, and the readers differ greatly in taste and requirements. Some fairy books are worse than useless to the folklorist, books in which the authors treat their sources in a thoroughly irresponsible fashion. On the other hand, those who could handle such materials discreetly, learnedly, and reverently cannot be induced to write fairy books. But such books must be written, and Mr. Graves has produced one which is in every respect commendable ... Many of the tales are in proper form for scientific examination, being evidently faithful records of oral traditions ... As in Welsh folklore, the fairies are in high glee at the seasonal festivals. Puck, for instance, is definitely associated with November. Lugnassed, Lug's marriage — the old name for the August festival — survives in dialect as "Lunacy day in harvest."

From *Nature* 24 February 1910.

formula that describes the relationship between the system's thermodynamic parameters, such as pressure, volume, temperature and internal energy. From the history of physics, we know that a new formulation or modification of a system's equation of state represents an advance in our understanding of the system. The most famous equation of state, the ideal-gas law, was formulated in the early 1800s. It describes the state of an ideal gas, a hypothetical gas composed of non-interacting point particles. Despite its simple form ($PV = nRT$, where P is the pressure, V the volume, n the density, T the temperature and R a constant) the ideal-gas law provides a good description of the behaviour of many ordinary gases under normal conditions.

The procedure to obtain the equation of state for a gas is straightforward: fill a box with a 'cloud' of gas; measure how its pressure changes with temperature or volume, or vice versa; do so for all possible phases of the system; and, finally, combine and translate all of the information into an equation. In their experiment, Nascimbène *et al.*[3] did just that, but with two differences. First, their sample, a fermionic gas of lithium-6 atoms in a mixture of two spin states, was confined in a harmonic trap instead of a box. Second, they measured the shape — that is, the gas density distribution — of the cloud.

In a harmonic trap, the trapping potential changes quadratically as a function of distance from the trap centre, so a sample in the trap has an inhomogeneous density distribution: a high density at the centre and a low density in the outer regions. As a consequence, the phase of the system varies spatially across the sample. This spatial inhomogeneity makes it difficult to measure the thermodynamic properties of the system, and so the equation of state. However, because in thermal equilibrium neighbouring local points in the sample have a well-defined thermodynamic relationship, it turns out that from the precise measurement of the gas density distribution one can access the thermodynamic quantities[4]. Nascimbène and colleagues measured the equation of state for the gas in the unitary regime for both a spin-balanced (with no net spin) sample at finite temperature and a spin-imbalanced sample in the zero-temperature limit.

Interestingly, the authors find that the thermodynamic behaviour of the normal (non-superfluid) phase of the gas in the unitary regime, for both balanced and imbalanced samples, is very close to that of a Fermi liquid. In the BEC regime, fermions pair up and form spatially localized molecules before undergoing a phase transition to a superfluid; the low-temperature normal phase is a Bose liquid of thermal molecules. In the BCS regime, fermion pairing and superfluidity occur at the same time, so the normal phase is a Fermi liquid of atoms (Fig. 1). In attempts to model the BCS–BEC crossover, theorists have anticipated that the normal phase of Fermi gases in the unitary limit might be a non-Fermi-liquid phase such as the pseudo-gap state that is

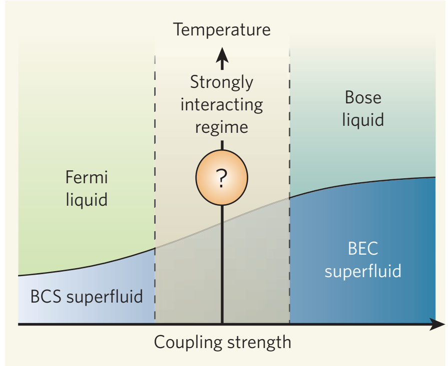

Figure 1 | Nature of the strongly interacting regime. A strongly interacting Fermi gas lies at the crossover between a Bardeen–Cooper–Schrieffer (BCS) superfluid and a Bose–Einstein condensate (BEC) superfluid. As the coupling strength between particles is increased, the BCS superfluidity (frictionless flow) of weakly interacting pairs of fermions (Cooper pairs) smoothly evolves into the BEC superfluidity of tightly bound bosonic molecules made of fermions. In the BEC regime, the low-temperature normal (non-superfluid) phase is a Bose liquid of molecules; in the BCS regime, the low-temperature normal phase is a Fermi liquid of atoms. Nascimbène *et al.*[3] demonstrate that the hitherto uncharacterized normal phase of a strongly interacting Fermi gas in the unitary regime is very close to a Fermi liquid.

thought to be a precursor phase of the high-temperature superconducting state of copper oxide compounds[5]. Nascimbène and colleagues' experiment now shows unambiguously that this is not the case.

One novelty of their experiment lies in the use of a Bose gas to measure the temperature of the system. Lack of accurate thermometry has long been the bottleneck for determining the thermodynamic properties of strongly interacting Fermi gases. The observation of a lattice of vortices in such a system has provided conclusive evidence of high-temperature superfluidity[6]. But until now, the critical temperature at which a balanced Fermi gas becomes superfluid has not been determined in a model-independent way. Because the heat capacity of ultracold (nanokelvin temperature) atomic gases is extremely small, a normal thermometer cannot be used as the sample would immediately vaporize. Inspired by an earlier demonstration[7], Nascimbène *et al.*[3] overcome this problem by introducing a small amount of a Bose gas into the sample and measuring its temperature. The Bose gas used by the authors has the advantage of being sufficiently weakly interacting to not perturb the sample, but strong enough to be in thermal equilibrium with it. This technique allowed the researchers to measure the temperature of their samples directly.

Ultracold atomic-gas systems have been developed to simulate a variety of quantum phenomena and to tackle long-standing problems in condensed-matter physics. Nascimbène and colleagues' determination of the equation of state for a unitary Fermi gas represents an outstanding example of quantum simulation, providing valuable qualitative and quantitative information on a regime for which a comprehensive theoretical description is inevitably difficult. In the long run, their technique might be generalized to all other cold atomic systems and become a useful tool with which to probe thermodynamic properties and thus search for exotic quantum states of matter. ■

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1. Ho, T.-L. *Phys. Rev. Lett.* **92,** 090402 (2004).
2. Inguscio, M., Ketterle, W. & Salomon, C. Ultracold Fermi Gases *Proc. Int. School Phys.* "Enrico Fermi" Course CLXIV (IOS Press, Amsterdam, 2008).
3. Nascimbène, S., Navon, N., Jiang, K. J., Chevy, F. & Salomon, C. *Nature* **463,** 1057–1060 (2010).
4. Ho, T.-L. & Zhou, Q. *Nature Phys.* **6,** 131–134 (2010).
5. Chen, Q., Stajic, J., Tan, S. & Levin, K. *Phys. Rep.* **412,** 1–88 (2005).
6. Zwierlein, M. W., Abo-Shaeer, J. R., Schirotzek, A., Schunck, C. H. & Ketterle, W. *Nature* **435,** 1047–1051 (2005).
7. Spiegelhalder, F. *et al. Phys. Rev. Lett.* **103,** 223203 (2009).

REGENERATIVE MEDICINE

Cell reprogramming gets direct

Cory R. Nicholas and Arnold R. Kriegstein

In a feat of biological wizardry, one type of differentiated cell has been directly converted into another, completely distinct type. Notably, the approach does not require a stem-cell intermediate stage.

Barriers to transdifferentiation — the direct conversion or reprogramming of one cell type into another — are falling fast. On page 1035 of this issue, Vierbuchen *et al.*[1] maintain the pace of this research by describing a potential innovation for generating disease-specific and patient-specific tissues of the central nervous system (CNS) that does not rely on stem cells. The route to possible regenerative-medicine-based treatment of CNS disorders such as epilepsy, stroke and Parkinson's disease may have taken another unexpected turn.

In 2006, the ability to reprogram fibroblasts, a type of cell found in connective tissue throughout the body, to embryonic-like stem cells (called induced pluripotent stem, iPS, cells)[2] was a breakthrough: it cleared the way to create disease- and patient-specific stem cells and sidestepped the thorny ethical issues associated with embryonic stem (ES) cells from human embryos. Disease-specific iPS cells, derived from patients with specific genetic disorders, such as some cases of amyotrophic lateral sclerosis (Lou Gehrig's disease), are already being used to study disease mechanisms and to search for new drug targets. Patient-specific iPS cells hold the promise of replacement-cell therapy without the risk of immune rejection. But such are the developments in cell transdifferentiation[1,3] that one might ask if stem cells will be dispensable in the quest for regenerative medicine.

It was once thought that cells are irreversibly instructed to become specific cell types in the body. We now know that this is not the case. Reprogramming of cell fates began with work in the 1960s that harnessed the ability of the oocyte (egg) to instruct differentiated adult cell nuclei to revert to an undifferentiated state. This process, called somatic-cell nuclear transfer (SCNT)[4], can result in an embryo and ES cells with the genetic make-up of the adult cell. Similarly, fusing ES cells with adult cells can convert the adult cell nucleus to an undifferentiated state[5] (Fig. 1). But the clinical relevance has remained doubtful: human SCNT has not yet succeeded, and cell fusion results in tetraploidy, a clinically unacceptable duplication of nuclear material.

The 2006 paper[2] boosted the reprogramming field with the discovery that adult fibroblasts can be induced to undergo a dramatic cell-fate reversal to an undifferentiated iPS cell state through the transient expression of four master-regulatory genes that encode transcription factors. The iPS cell approach has unquestionable clinical relevance. But adult cells must first be completely de-differentiated to an ES-cell-like state, and then subsequently re-differentiated to an adult cell type of interest — a time-consuming and inefficient detour (Fig. 1).

This detour raised the question of whether cell reprogramming could be optimized by directly inducing other adult cell fates without complete de-differentiation. Transdifferentiation of mammalian cells took a knock when reports of lineage reprogramming turned out to represent cell fusion[6]. But other studies suggested that conversion of one cell type to another could be achieved by activation of a few core factors[7]. An especially notable advance was the 2008 discovery[3] that transient activation of three transcription factors induced the direct reprogramming of pancreatic exocrine cells into insulin-producing endocrine cells with robust (20%) efficiency. In this and most other studies, however, reprogramming occurred only between closely related cell lineages.

This is where Vierbuchen and colleagues[1] come in. Beginning with a set of 19 candidate genes that encode transcription factors involved in neuronal development or function, they eventually found that a combination of only three factors was sufficient to convert fibroblasts into neurons (Fig. 1). The fibroblasts were derived from mouse embryos and newborn or adult tail-tips of 'reporter' mice engineered to express a green fluorescent marker when the gene for the protein tau was turned on. Because

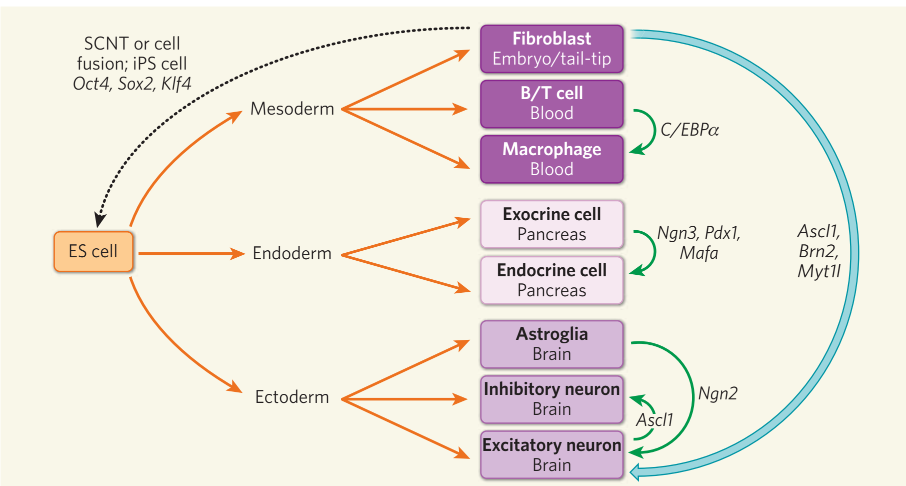

Figure 1 | Indirect and direct routes to cell-lineage reprogramming. The indirect routes involve reprogramming of a variety of adult cell types from different lineages to produce a de-differentiated embryonic stem (ES) cell state. Indirect routes (dotted arrow) include somatic-cell nuclear transfer (SCNT) or cell fusion, or creation of induced pluripotent stem (iPS) cells by the introduction of genes such as *Oct4*. But the de-differentiated cells must then be re-differentiated to adult cell types along the respective mesodermal, endodermal or ectodermal lineages. Vierbuchen *et al.*[1] demonstrate that a direct route can be taken (blue arrow): by inducing lineage-specific transcription factors encoded by genes including *Ascl1*, *Brn2* and *Myt1l*, they show that fibroblasts can be directly converted into distantly related cortical excitatory neurons. This is an advance over the intra-lineage conversion achieved between cells of the blood, pancreas or brain by induction of the other genes noted. Intra-lineage conversion studies not shown include fibroblast to macrophage and fibroblast to muscle cell by *PU.1* and *MyoD*, respectively.